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Going for Gold: A Path Toward Petroleum-Independence in the 2030 Air Force

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About the Author

Colonel Azzano is a student at the Air War College, Maxwell Air Force Base, Alabama. He is a career fighter pilot and test pilot with assignments in combat operations, flight test, acquisitions, headquarters staff, and the Combined Air Operations Center. He has participated in or directly supported Operations SOUTHERN WATCH, NORTHERN WATCH, IRAQI FREEDOM, and ENDURING FREEDOM. Colonel Azzano served as Operations Officer and Commander of flight test squadrons responsible for delivering combat capabilities to the Joint aviation community. He is a graduate of the Air Force Intern Program and an Air Force Legislative Fellow. His education includes a Bachelor's Degree in Aeronautics and Astronautics from Purdue University, a Master's Degree in Aeronautics and Astronautics from Stanford University, a graduate certificate in Organizational Management from George Washington University, and a graduate certificate in Legislative Affairs from Georgetown University. A Command Pilot with over 2600 hours in 30 aircraft types, Col Azzano will assume command of the 412th Operations Group, Edwards Air Force Base, California following Air War College.

Introduction

"…Energy security (is) a challenge…an enduring one for our military and our nation...there is a strategic imperative for us to reduce risk, improve efficiencies and preserve our freedom of action wherever we can…the time for change is now."[1]

- Admiral Mike Mullen, Chairman of the Joint Chiefs of Staff (October 2010)

Even as it projects power around the globe, the Air Force is becoming one of the United States' most troubling strategic vulnerabilities. Airpower's dependence on foreign oil threatens U.S. preeminence across the spectrum of future operations, with supply and price stability increasingly at risk. Reversing this ominous trend requires the Air Force to embrace next-generation technology to help *reduce* and *replace* the fuel currently consumed by aviation. By developing highly efficient aircraft and incorporating domestic alternative fuels, *the Air Force **can** break its addiction to oil and secure its energy independence*. Furthermore, the efficiency of tomorrow's fleet will have the salutary effect of dramatically reducing Air Force fuel expenses.

If energy is the feedstock of the global economy, America's favorite flavor is oil. Despite being home to only 4.5% of the world's population,[2] the United States is the top global oil consumer at almost 19 million barrels per day (2009).[3] Thus, 4.5% of the world's inhabitants consume over 22% of the world's petroleum.[4] Lacking the reserves and production capacity to sustain this rate of consumption, the United States must import over 50% of its petroleum.[5]

In the last few years, U.S. policy makers have devoted increased attention to the perils of petroleum dependence, their concerns punctuated in an October 2010 speech by the Chairman of the Joint Chiefs of Staff. Most importantly, heavy reliance on oil to power the military renders national security vulnerable to foreign suppliers who do not necessarily share U.S. values and interests.[6] Already threatened by huge emerging energy markets in China and India, oil supplies

are increasingly dependent on unstable regions of the globe, any of which could degrade the United States' ability to protect its interests (Figure 1).

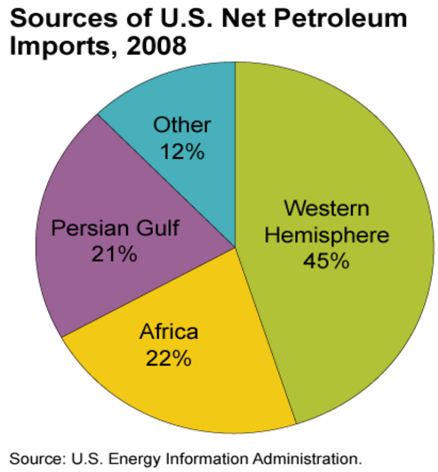

Figure 1: Sources of U.S. Petroleum Imports[7]

Additionally, as world energy demands begin to outstrip supply, the global market will likely encounter dramatic and unpredictable shocks that impose an unsustainable fiscal burden on the Department of Defense (DoD). In its Annual Energy Outlook 2010, the Department of Energy projected an upper bound on the price of oil in 2030 at over $200 per barrel (Figure 2).

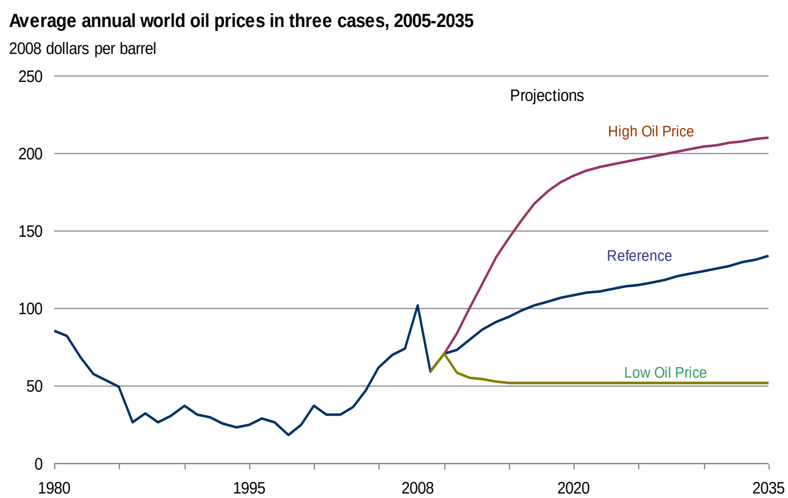

Figure 2: World Oil Price Trends **(source: Dept of Energy)**[8]

Increasingly constrained budgets would leave DoD hard-pressed to absorb such high petroleum costs while attempting to modernize and prepare for a spectrum of future threats.

Furthermore, as articulated by the Chairman in October 2010, the U.S. is beginning to see evidence of climate change impacting national security.[9] Although there is considerable disagreement over the causes, a growing body of scientific evidence suggests human-induced stress—including the release of greenhouse gases from petroleum combustion—is contributing to climate change in a way that compels immediate action. Prominent futurist Dennis Bushnell insists climate change represents the single greatest threat to national security.[10]

These three arguments have strong relevance from an airpower perspective, with supply and price stability in particular having direct impact on the core missions of the Air Force. A disruption in the flow of fuel at the theater level (Figure 3) or as a result of a global energy shortage could have a debilitating impact on every Air Force mission area. To make matters worse, an increasingly unstable petroleum supply will consume ever greater fractions of the Air Force budget. Unless senior leaders are willing to cede airpower's fate to an uncertain energy supply, they must eliminate Air Force dependence on foreign oil, and ideally on all forms of

Figure 3: NATO Fuel Truck Attacked by Militants in Afghanistan[11]
(source: Air Force Magazine.com)

petroleum energy for the three reasons articulated by the Chairman and echoed throughout DoD: 1) supply vulnerability, 2) fiscal uncertainty, and 3) environmental impact. This paper will focus on the first two arguments as the impetus for developing advanced technology, incorporating it into next-generation airframes, and striving for unprecedented levels of fuel efficiency.

Air Force Petroleum Consumption

The quantity and cost of petroleum consumed by the Air Force is staggering. With 64% of the DoD total, the Air Force is the largest consumer of petroleum in the federal government. Furthermore, 84% of Air Force energy costs are attributed to aviation alone (Figure 4). In fiscal year (FY) 2008, this equated to approximately 2.5 billion gallons of aviation fuel at a cost approaching \$9 billion.[12] At that level of consumption, each \$10 increase per barrel of oil results in a \$600 million increase in aviation fuel expenses.[13] These numbers paint a grim picture of Air Force reliance on petroleum—much of it foreign—to execute some of the nation's most important security directives. Fortunately, they also present an obvious target in the effort to eliminate a critical strategic vulnerability.

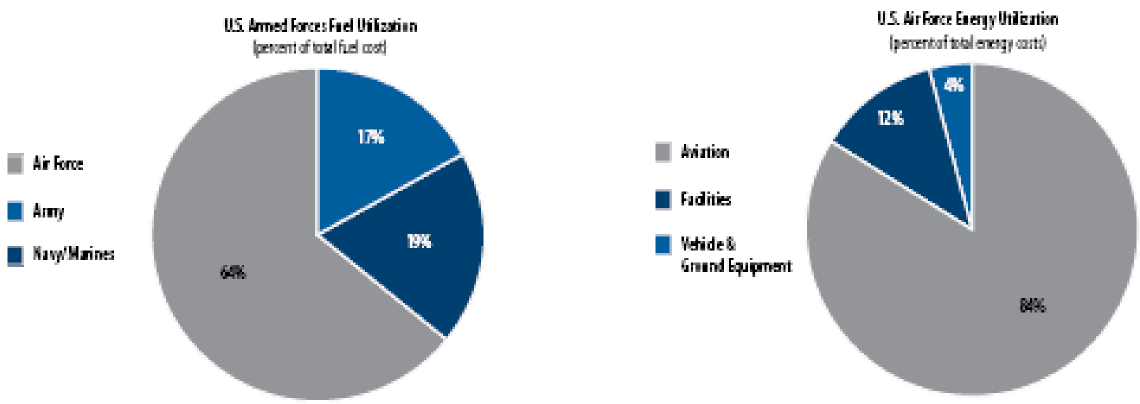

Figure 4: Breakdown of DoD & Air Force Petroleum Use in FY08[14]
(Source: Air Force Energy Plan 2010)

A closer look at aviation fuel consumption adds clarity to the problem of Air Force petroleum dependence. Based on average use from FY98-04, the *air mobility* mission accounts for over half the Air Force fuel requirements, with *fighter* aviation just under one third (Figure 5). Together, mobility, fighter, and bomber missions consume over 90% of Air Force jet fuel. Currently, all of it is petroleum based. Thus, breaking the petroleum addiction starts with an examination of the platforms that perform high-demand missions and the sources that supply their fuel.

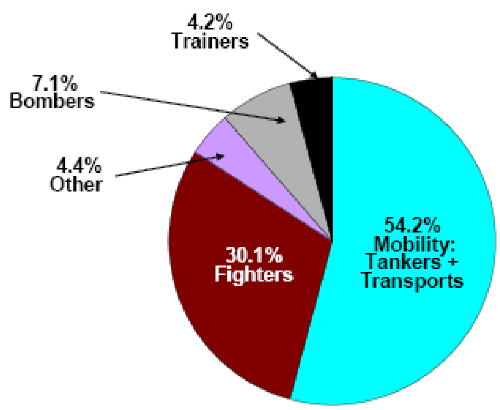

Figure 5: Air Force Aviation Fuel Consumption by Platform Type (FY98-04)[15]
(Source: Scientific Advisory Board)

Motivated by strategic, fiscal, and environmental imperatives, the 2010 Air Force Energy Plan defines three pillars for energy management: *reduce demand, increase supply,* and *culture change*.[16] Within this framework, the means for reducing demand generally fall into one of three categories: operations, maintenance, and technology. Route optimization and formation flight[17] are two operational initiatives with high potential impact. Seemingly insignificant maintenance practices can also take a sizeable bite out of fuel use, including periodic checks for proper flight control rigging and surface washing to minimize airframe drag. The most promising energy management roadmap, however, involves the application of advanced technology to reduce fuel

demands across the Air Force fleet, in conjunction with a transition to alternative fuels—fuels that are not petroleum based—to increase the overall fuel supply. Consequently, this study will focus on achieving petroleum independence through technological solutions, many of which should be available in the 2030 timeframe.

The Air Force has already made some progress in the fight to improve fuel efficiency and provide alternative fuel sources. The Air Force Research Laboratories and NASA have sponsored numerous initiatives to improve engine performance, increase aerodynamic efficiency, and reduce airframe weight. Furthermore, the effort to certify all Air Force platforms on a 50-50 blend of JP-8 and synthetic fuels is 85% complete, with a goal of clearing the entire fleet by 2011.[18] If the Energy Plan meets its objective of using fuel blends to supply 50% of aviation fuel by 2016,[19] the Air Force will be half-way toward eliminating its vulnerability to *foreign* petroleum supplies. Technology has real potential to eliminate the other half, while dramatically reducing the overall fiscal and environmental burdens of Air Force aviation. Securing energy independence in this manner would ensure stable, domestic fuel sources, enabling operations expenses to be accurately budgeted years in advance.

"Great Tech…Less Fueling!"

Developing the right blend of next-generation technology could dramatically reduce AF fuel consumption in the 2030 timeframe. Some technologies already show great promise and should be available in the near future, with possible application to legacy systems. Others are still early in the development cycle and may require years to mature. Those with the highest technical risk look like science fiction today, some having barely left the drawing board.

Mindful of the variability in technical risk and developmental timelines, this paper presents the author's view of the most promising fuel conservation technologies in the next 20 to 30 years when many legacy systems will be replaced. Because the aerospace sciences evolve unpredictably, the author selected *high-payback technologies* that can realistically be engineered into next-generation Air Force platforms. The choice of technologies, though not exhaustive, represents one possible path toward a more fuel efficient future.

Technology Maturity and the "S-Curve"

The life-cycle of a technology can be described in three stages: *slow growth* (the early phase), *rapid growth* (the exponential phase), and *leveling off* (the mature phase).[20] Viewed over time, the combination of these stages looks like a letter "S" on an x-y graph (Figure 6). The conceptual value in an "S-curve" analysis of technology is powerful—a technology that is lower on the curve (just entering the *rapid growth* phase) has more potential payback, regardless of technical risk. Conversely, a technology in the *leveling off* phase (high on the curve) has reached a point of diminishing returns. Obviously, fuel conservation technologies that merit the greatest investment today are those that are still relatively low on the S-curve, offering high potential for long-term payback.

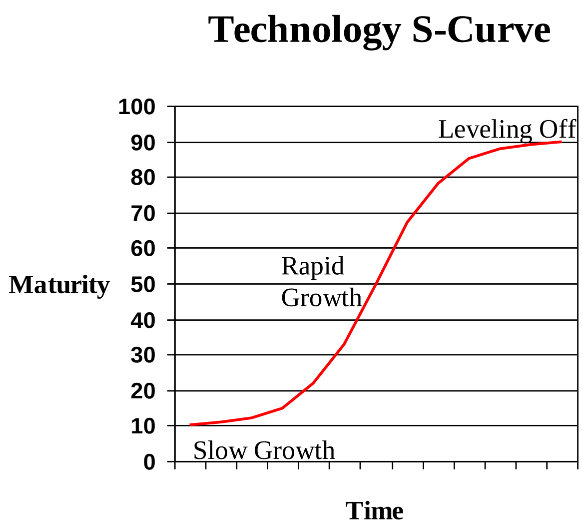

Figure 6: Technology S-Curve Illustration

This study is built on extensive research and consultation with government, industry, and academic experts to identify the most promising potential improvements in fuel efficiency for the 2030 Air Force. Comparing modern science with projections out to 2030 and beyond provides a snapshot of technology S-curves today. A more accurate assessment of technical maturity is only available after the fact when a technology has reached the "leveling off" phase. Thus the S-curve estimates associated with each technology in this report are derived from the educated opinions of the author and industry professionals.

Parameters Affecting Fuel Consumption

To understand how technology can improve fuel efficiency, it is useful to consider the impact of classic design factors on aircraft performance. Within the engineering community, the "Breguet range equation" is commonly used to relate the approximate range of an aircraft in cruise conditions to its configuration, flight parameters, and weight fractions (Figure 7).[21] Since most Air Force aircraft expend the bulk of their fuel in cruise, the Breguet equation can help

identify high-payback technologies. Furthermore, because the scientific relationships extend to other phases of flight such as climb, descent, and loiter, the Breguet equation can point toward technologies that enhance fuel efficiency across the spectrum of mission tasks, reducing overall Air Force fuel requirements proportionally.

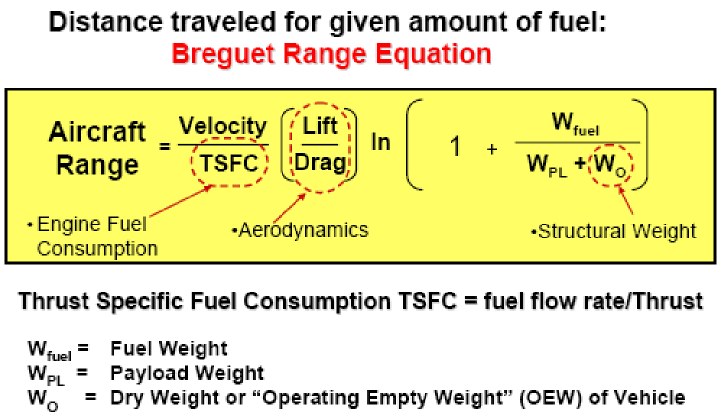

Figure 7: The Breguet Range Equation[22]
(Source: Scientific Advisory Board)

Though scientifically grounded in the Breguet equation, the relationships between design factors and fuel consumption are intuitive on their own: more efficient engines, better aerodynamics, and reduced structural weight improve fuel efficiency. Despite the trade space between range, fuel load, and payload weight, it is nevertheless useful to think of the opportunities for fuel conservation in this context. Therefore, for the purpose of this study, next-generation fuel efficient technologies will be classified into one of three categories:[23]

1) *Structural Weight Reduction*

2) *Improved Aerodynamics*, and

3) *Enhanced propulsion efficiency*.

Some of the most promising technologies in each category are listed in Table 1. They were assessed according to long-term payback potential, fiscal viability, and technical risk.

Furthermore, the author attempted to place each technology on its S-curve as of this writing. Though lacking statistical rigor, the estimates for technical maturity are based on considerable research and consultation with subject matter experts. These technologies form the basis for the remainder of this paper, and constitute the foundation for a viable path to petroleum independence in the 2030 Air Force.

Category	Technology	S-curve Maturity
Structural Weight Reduction (W_O)	Design Optimization	**Rapid Growth**
	Active Aeroelastic Control	**Rapid Growth**
	Advanced Materials	**Slow Growth**
Improved Aerodynamics (L/D)	Conventional Configurations	**Leveling Off (overall)**
	Natural Laminar Flow	**Rapid Growth**
	Adaptive Compliant Structures	**Rapid Growth**
	Novel Configurations	**Slow Growth**
Enhanced Propulsion Efficiency (TSFC)	Conventional Gas Turbine Engines	**Leveling Off**
	Hybrid Gas Turbine Engines	**Slow Growth**
	Energy Capture/Storage	**Slow Growth**
	Alternative Fuels	**Rapid Growth**

Table 1: Promising Technologies for Fuel Efficiency in the 2030 Timeframe

Structural Weight Reduction

Design Optimization. Advanced methods will allow for structural optimization and use of custom materials to reduce the design margin and weight of future aircraft, even with "off-the-shelf" materials in common use today. Studies have reported significant reductions in empty weight (10-15%)[24] and reduced manufacturing cost and complexity[25] as a result of advanced optimization and fabrication methods. These techniques will almost certainly have a significant impact on future fuel efficiency, further enhancing next-generation designs that incorporate advanced materials and active structural control.

Active Aeroelastic Control. Active control of airframe structures subjected to aeroelastic effects (the interaction between aerodynamic forces and flexible structural components) constitutes another promising area for reducing structural weight. Particularly with high aspect ratio wings and flying wing aircraft, conventional structures are "over-designed" in order to provide the strength and stiffness to control flutter. A study sponsored by AFRL investigated active suppression of wing flutter with control surfaces to supplement structural stiffness. The analysis revealed a 19% reduction in wing weight for high aspect ratio wings and flying wing configurations.[26] Applied to conventional configurations, the weight savings could approach 5% for transport aircraft and MQ-9 class UAVs.[27] The weight dividend for tactical aircraft would be less significant, since peak g-loading is the primary driver of wing design.

Advance Materials. Aircraft manufacturers have been using carbon fiber composites extensively for decades, but there is still tremendous potential to integrate stronger, lighter materials into airframe structures. The composites boom was fueled by high-strength, lightweight carbon fiber reinforced polymers which were introduced into more and more aircraft components as manufacturers and their customers became comfortable with their use. The Boeing 787 now leads the transport class at approximately 50% structural composites by weight,[28] with the state-of-the-art F-35 incorporating approximately 35%.[29]

Looking forward 20-30 years, the next generation of composites could incorporate high-strength "nano-enabled" materials such as carbon nanotubes (CNTs). First discovered in 1991, CNTs are thought to be 50 to 100 times stronger than steel and half the weight of aluminum.[30] Despite significant technical challenges, researchers have succeeded in "yarning" CNTs together to form the building blocks for future ultra-high strength materials. Carbon nanotube yarns are even available commercially today.[31] Furthermore, research sponsored by NASA hopes to

"grow" structures entirely from CNTs and boron nitride nanotubes, offering the potential for another incremental jump in strength-to-weight ratio of aircraft materials.[32]

To evaluate the impact of CNT materials on structural weight, one study suggests substituting a notional CNT reinforced polymer (CNRP) for aircraft structural aluminum.[33] This methodology bypasses a component level analysis, but probably yields a conservative weight estimate since CNRP strength would allow many components to be engineered to a smaller size. This methodology also provides a simple way to estimate the impact of CNRP properties throughout the aircraft structure, a reasonable objective given industry's success in fabricating most major structural components from present day composites.[34] Consequently, volumetric replacement of structural aluminum appears to yield a useful estimate of the impact of nano-enabled materials on structural weight.

Category	*Technology*	*S-curve Maturity*
Structural Weight Reduction (W_O)	Design Optimization	Rapid Growth
	Active Aeroelastic Control	Rapid Growth
	Advanced Materials	Slow Growth
Improved Aerodynamics (L/D)	**Conventional Configurations**	**Leveling Off (overall)**
	Natural Laminar Flow	**Rapid Growth**
	Adaptive Compliant Structures	**Rapid Growth**
	Novel Configurations	**Slow Growth**
Enhanced Propulsion Efficiency (TSFC)	Conventional Gas Turbine Engines	Leveling Off
	Hybrid Gas Turbine Engines	Slow Growth
	Energy Capture/Storage	Slow Growth
	Alternative Fuels	Rapid Growth

Table 1a: Promising Technologies for Fuel Efficiency in the 2030 Timeframe

Improved Aerodynamics

Conventional Configurations—Natural Laminar Flow. Increasing the area of laminar flow on aircraft wings and tail surfaces could reduce parasite drag and lead to a significant

improvement in aircraft fuel efficiency. A turbulent boundary layer (the layer of flow between the free stream air and aircraft skin) can produce 10 times the localized drag as laminar flow.[35] Through a variety of methods including airfoil design and distributed surface roughness, laminar flow on the upper surface can be extended beyond the range of conventional airfoils. One AFRL study reported a 17% reduction in parasite drag using these methods (12% wing, 5% tail).[36] Supporting research by Boeing predicted an 11-14% improvement in lift-to-drag ratio (L/D) from today's configurations.[37] As design, manufacturing, and maintenance methods improve, it is reasonable to expect this type of dividend across much of the high-aspect-ratio fleet. Tactical aircraft will probably benefit less from laminar flow technology, having thinner wings and a wider airspeed range for typical mission profiles.

Conventional Configurations—Adaptive Compliant Structures. Another technology with significant potential to improve fuel efficiency would optimize wing airfoil shape across the aircraft flight envelope. Modern, fixed airfoils are sized and shaped for their "design" condition; any departure from those parameters in flight results in an L/D penalty. Since mission constraints rarely allow an aircraft to operate at its exact design condition, a cumulative penalty in induced drag increases fuel consumption over the course of a mission.

AFRL's Mission Adaptive Compliant Wing (MACW) program is investigating methods to optimize airfoil shape across a wider range of flight conditions. One solution takes advantage of mechanically "compliant" structures internal to a flexible trailing edge of the wing to reshape the upper and lower surface, maximizing L/D for the actual flight condition (Figure 8). Absent an inherently flexible structure, the method for "morphing" the wing could involve a significant weight penalty. Given MACW's lightweight approach, however, the 15% improvement in L/D

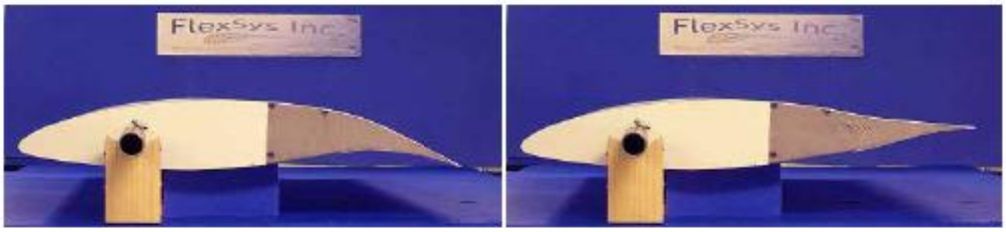

Figure 8: Mission Adaptive Compliant Wing (made for AFRL by FlexSys Inc)[38]

measured in actual flight test should come with minimal added weight.[39] If the MACW program is able to demonstrate scalability in the next 5-10 years, similar L/D improvements could be engineered into large airframes by 2030.

Novel Configurations. For years, aircraft designers have been intrigued by the theoretical performance benefits of unconventional aircraft configurations (non-tube-and-wing), but have found little traction for their ideas among commercial or military customers. Until recently, even technology demonstrators were limited in number, NASA's oblique wing AD-1 being a prominent exception (Figure 9). With the looming petroleum crisis, however, now may be the time to move beyond the stigma of strangely proportioned air vehicles to reap the rewards of designs that feature revolutionary improvements in aerodynamics.

Figure 9: NASA AD-1 Oblique Wing Demonstrator[40]
(Source: NASA Dryden Flight Research Center)

The blended wing-body (BWB) design, in particular, has been gaining attention as a candidate for next-generation transport aircraft. Co-sponsored by AFRL and NASA, the X-48 is a subscale BWB technology demonstrator (Figure 10). The X-48 has shown exceptional aerodynamic characteristics throughout a multi-year flight test program. In one conservative baseline mission, it demonstrated a 58% reduction in fuel burn relative to its conventional counterpart,[41] supporting the general belief among BWB advocates that a 25% improvement in lift-to-drag ratio is well within reach.[42]

Figure 10: Boeing's X-48 Blended Wing-Body Technology Demonstrator[43]
(Source: NASA Dryden Flight Research Center)

The blended wing-body is representative of several novel configurations under development that could provide similar benefits across the transport, bomber, and high-dwell intelligence-surveillance-reconnaissance (ISR) fleets in the 2030 timeframe. Bringing a revolutionary design into production will require extensive research and development, and could face obstacles in the Federal Aviation Administration (FAA) certification process. Nevertheless, these concepts should be considered for their long-term benefit to Air Force fuel conservation.

Category	Technology	S-curve Maturity
Structural Weight Reduction (W_O)	Design Optimization	Rapid Growth
	Active Aeroelastic Control	Rapid Growth
	Advanced Materials	Slow Growth
Improved Aerodynamics (L/D)	Conventional Configurations	Leveling Off (overall)
	Natural Laminar Flow	Rapid Growth
	Adaptive Compliant Structures	Rapid Growth
	Novel Configurations	Slow Growth
Enhanced Propulsion Efficiency (TSFC)	Conventional Gas Turbine Engines	**Leveling Off**
	Hybrid Gas Turbine Engines	**Slow Growth**
	Energy Capture/Storage	**Slow Growth**
	Alternative Fuels	**Rapid Growth**

Table 1b: Promising Technologies for Fuel Efficiency in the 2030 Timeframe

Enhanced Propulsion Efficiency

Conventional Gas-Turbine Engines. Although conventional gas-turbine engines appear to be “leveling off” in maturity, experts believe there is still significant room for improving gas-turbine fuel efficiency. *Thrust specific fuel consumption* (TSFC), a widely used measure of fuel economy, has steadily improved since gas-turbine engines gained widespread use in the 1950s. Incremental improvements have been hard-won in recent years (Figure 11 shows the “leveling off” trend), but a number of relatively new research and development initiatives promise to continue delivering cost-effective enhancements.

Future reductions in TSFC for conventional gas-turbines will depend on three design factors: 1) bypass ratio, 2) turbine inlet temperature, and 3) overall pressure ratio.[44] Historically, some of the greatest improvements in TSFC were the result of increased bypass ratios on externally mounted, big inlet turbofans. Further reductions in TSFC will require advancements in turbine inlet temperature and overall pressure ratio, presenting an opportunity for dual-use technology benefiting the low-bypass fighter and bomber engine categories as well.[45]

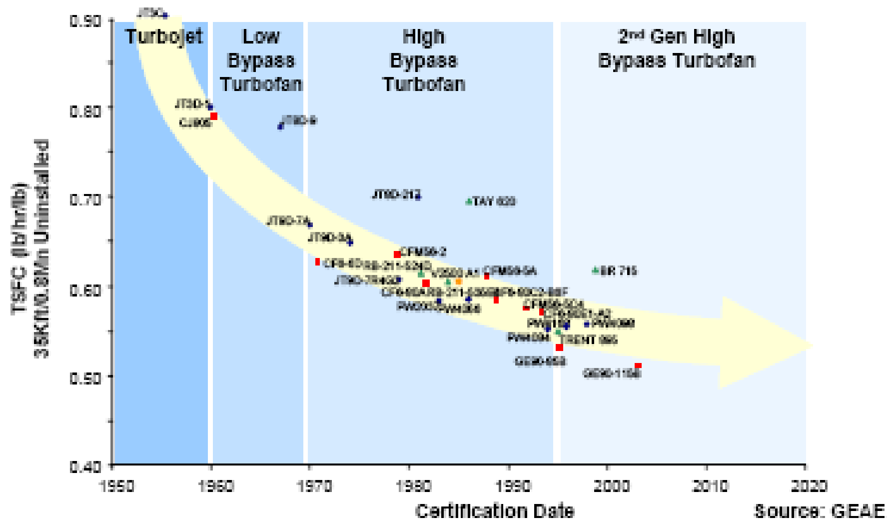

Figure 11: Evolution of Gas-Turbine Fuel Efficiency[46]
(Source: GE Aircraft Engines, through Scientific Advisory Board)

The Versatile Affordable Advanced Turbine Engine (VAATE) program, jointly sponsored by AFRL, NASA, and industry, has specific goals for TSFC improvement with application to multiple turbine engine classes. Within VAATE, a subsidiary research effort known as ADVENT (Adaptive Versatile Engine Technologies) is investigating engine cycle optimization across a wide range of flight conditions. Its signature concept is adaptive control of airflow between the engine core and fan, enabling one engine to perform both high-thrust and long-endurance tasks, depending on mission requirements.[47]

Despite daunting technical challenges, several recent advances in high temperature materials, innovative cooling mechanisms, improved component efficiencies, and adaptive technologies should help next-generation engines achieve significant improvements in performance. One AFRL expert cites multiple studies and research efforts to project the following TSFC reductions for gas-turbine engines in the 2030 timeframe:

1) Mobility (C-17 class): 15%

2) Fighter, subsonic (F-22 class) and Bomber (B-2 class): 20%

3) Fighter, supersonic (F-22 class): 10%.[48]

Another government study forecasts similar gains in the efficiency of turboprop engines:[49]

4) UAV (MQ-9 class): 25%.

Synthesized with reduced airframe weight and improved aerodynamics, conventional gas-turbine engine technologies stand to make a big dent in Air Force petroleum use. Even greater gains may be possible with novel engine concepts.

"Hybrid" Gas-Turbine Engines. Hybrid engines could one day provide a dramatic boost in fuel efficiency for much of the Air Force fleet. The Air Force Energy Plan 2010 specifically identifies "hybrid energy systems" as a means to increase range and loiter capabilities.[50] A Boeing team sponsored by NASA describes hybrid engines as high-risk, high-payoff, but a "clear winner" from the standpoint of potential performance improvements.[51]

Like the blended wing-body aircraft configuration, hybrid gas-turbine technology has not progressed much beyond the conceptual stage. Consequently, building a functional hybrid aircraft engine will require ground-breaking research and development with significant technical risk. One concept proposed by General Electric uses the core from its state-of-the-art high-bypass engine modified with an electric motor to help drive a larger fan. In theory, the fan could operate in all-turbine, all-electric, or combined modes, providing high-thrust on demand but fuel efficient cruise, using predominantly electric power for shorter range missions.[52]

This type of hybrid propulsion would offer the flexibility of operating partially or completely on electric power, but the source of that electricity remains one of the concept's more daunting technical challenges. Electric power could be drawn from batteries, captured energy, or a system which integrates both sources and also recharges batteries when captured energy exceeds total system demands.[53, 54] Aircraft with large thrust requirements would need super-

charged batteries and the payload capacity to carry them. Nevertheless, one study concluded that a 21% reduction in relative energy is representative of the effects of hybrid propulsion on the mobility mission, assuming battery technology in 2030-2050 lives up to expectations.[55] Future energy efficient UAV concepts might also benefit from captured energy.[56] Regardless of the energy fraction contributed by electric power, the reduced demand on liquid fuels would provide mission planners an enviable tradeoff between increased range and payload.

Energy Capture/Storage. There are numerous sources of energy in the environment to capture and convert to electrical energy for hybrid gas-turbine propulsion. Advanced piezo-electric technologies might one day capture energy from vibrating aircraft structures.[57] Another concept would recapture lost combustion heat from within the engine, potentially recovering up to 5% of fuel energy as electricity.[58] Energy could also be captured by a hybrid gas-turbine fan from airspeed bled off during approach and landing, similar to the energy captured while braking a hybrid automobile.[59]

Probably the most promising source of captured energy, however, is the sun. Advanced photovoltaic systems of the future could generate 1 kilowatt of energy per kilogram of high-efficiency material in full sunlight at a reduced weight of 300g per square meter.[60] These panels currently operate at about 30% efficiency, but technology could increase efficiency another 30% in the near future.[61] Furthermore, researchers believe nano-scale materials and a technique known as “light trapping” could absorb ten times more energy than the theoretical limit as it is understood today.[62] Though environmental stresses would remain a major technical challenge, efforts are underway to harden high-efficiency, flexible solar panels for use in aviation.[63]

For hybrid gas-turbine propulsion to achieve widespread use in larger aircraft, the scientific community must deliver a sizeable increase in the energy density of batteries. The

state of the art in battery storage is .128 kilowatt-hours per kilogram (kW-h/kg) for the most advanced Lithium Ion batteries.[64] Future nano-materials could boost storage capacity an order of magnitude by increasing the surface area of the electrode material in the battery.[65] Capacities on the order of 1.5kW-h/kg in the 2030-50 timeframe[66] would allow a larger class of aircraft to derive propulsive energy from electric power.

Alternative Fuels. Even the most optimistic improvements in fleet efficiency won't eliminate the Air Force's appetite for jet fuel. The demands of tomorrow's aircraft must be met by domestic energy to ensure a stable supply and price, which will drive the market toward non-petroleum based sources. Though alternative hydrocarbon fuels will have little impact on the propulsive efficiency of aircraft engines, they nevertheless constitute the cornerstone of any policy to eliminate Air Force dependence on foreign petroleum.[67]

There are four domestic resources with the potential to satisfy fuel demands in 2030: oil shale, coal, natural gas, and biomass. Oil shale is already approved as a feedstock for conventional refinement. Coal, natural gas, and biomass, however, must first be "gasified" and converted into a hydrocarbon product via the Fischer-Tropsch (F-T) process. The waxy F-T output is refined conventionally into aviation fuel.[68]

Supply and compatibility are two of the biggest hurdles to alternative fuel use in aviation. With the entire Air Force fleet on track for 50-50 JP-8/F-T certification by 2011, many of the compatibility issues are already being addressed.[69] Increasing the fraction of F-T in future fuel blends will require further study. In terms of supply, all three F-T feedstocks could deliver large quantities of alternative fuels, but at a cost of billions of dollars in refinement capacity.[70] An early commitment by the Air Force will kick-start the industry, creating a demand for alternative fuels that motivates government and private investment to develop the infrastructure.

Tomorrow's Air Power: Thirsty, yet Refined

To evaluate technology's impact on Air Force petroleum dependence, this study examines baseline aircraft from the four primary mission areas: *mobility, fighter/attack, long-range strike,* and *persistent ISR*.[71] Using a representative subset of the Air Force inventory, an analysis of the greatest petroleum consumers reveals trends in fuel consumption that could reflect the Air Force of 2030 recapitalized with next-generation platforms.

By necessity, this analysis includes simplifying assumptions which may justify additional investigation into the aggregate effects of enhanced fuel efficiency.[72] The numerical estimates of fuel savings are not intended to predict the actual performance of the 2030 inventory, but rather to give decision makers an idea of the macro-level impact of today's research and development investment. The state of the fleet in 2030 will depend strongly on adequate resourcing and senior level emphasis.

Breakthroughs in the aerospace sciences are often tailored to specific airframes and mission areas, and may not be suitable across the entire fleet. Table 2 matches promising next-generation technologies to the 2030 mission areas according to technical viability. It assumes an aggressive research and development investment today, and accounts for the fact that fewer technologies are adaptable to aircraft with unique planform and payload requirements. For example, hybrid propulsion requires aircraft that can accommodate high-bypass, open-fan, or turbo-prop engines. Also, despite being an attractive long-term solution to petroleum dependence, energy capture will probably have minimal impact in the 2030 timeframe unless solar cells improve dramatically. Stealth requirements impose additional constraints to technology suitability, particularly among combat aircraft.

Category	Technology	Mission Area			
		Mobility	Fighter/Attack	L-R Strike	ISR
Structural Weight Reduction	Design Optimization	X	X	X	X
(W_O)	Active Aeroelastic Control	X		X	X
	Advanced Materials	X	X	X	X
Improved Aerodynamics	Natural Laminar Flow	X	X	X	X
(L/D)	Adaptive Compliant Structures	X			
	Novel Configs	X		X	X
Enhanced Propulsion	Conventional Gas Turbine Engines	X	X	X	X
Efficiency (TSFC)	Hybrid Gas Turbine Engines	X			X
	Energy Capture/Storage				X
	Alternative Fuels	X	X	X	X

Table 2: Technology Suitability in 2030, by Mission Area

Given the complex interaction between aircraft design factors, the benefits of next-generation technology must be carefully synthesized to project a more accurate cumulative fuel savings. In this analysis, individual technologies are first integrated within each category.[73] To avoid inflating the "bottom line", the effects of each category are then combined using the Breguet equation to contrast the more fuel-efficient 2030 aircraft with today's technology.

A summary of improvements in fuel efficiency for the 2030 mission areas is listed in Table 3 for two levels of technology risk.[74] The cumulative benefits reflect only the subset of

Design Factor	Fuel Savings in 2030 (%)			
	Mobility	Fighter/Attack	L-R Strike	ISR
Structural Weight	25%	15%	16%	8%
Conventional Aerodynamics	15%	5%	10%	10%
Conventional Propulsion	15%	18%	20%	25%
Weight + Aero + Propulsion (Lower Risk)	**45%**	**33%**	**39%**	**37%**
Novel Configurations	25%	n/a	25%	25%
Hybrid Propulsion	20%	n/a	n/a	25%
Energy Capture/Storage	n/a	n/a	n/a	8%
Weight + Aero + Propulsion (Higher Risk)	**52%**	n/a	**46%**	**51%**

Table 3: Fuel Savings in 2030, by Mission Area (ref Appendix A)

technologies examined in this paper, but are nevertheless quite promising. Depending on the level of research and development investment and DoD's appetite for programmatic uncertainty, the results from this mission-area analysis could reflect an achievable benchmark for aircraft rolling off the assembly line in 2030.

A more intuitive presentation of fuel savings in 2030 graphically compares fuel requirements for a highly efficient fleet to 2010 consumption levels. Figure 12 illustrates the savings increment due to each of the three technology areas. After applying all three to the 2010 baseline fleet (100%), the remaining demands (diagonal blue pattern) represent fuel requirements

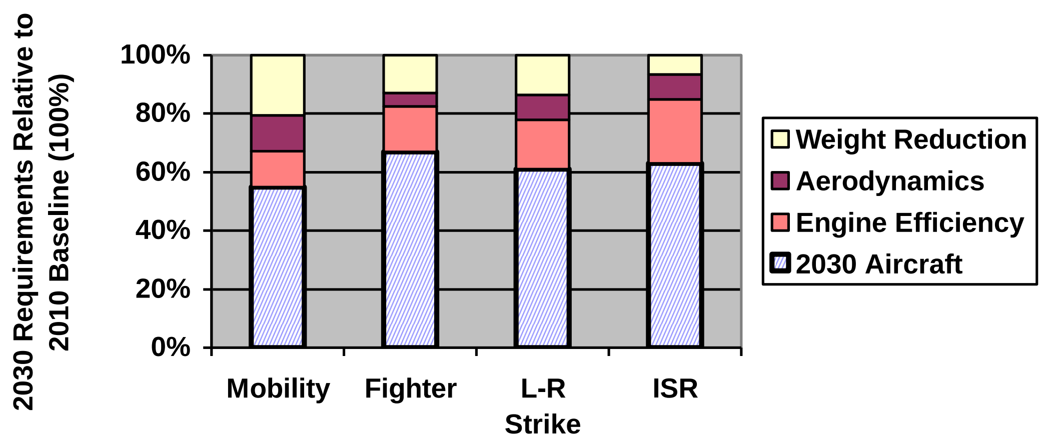

Figure 12: "Lower Risk" Technology-Based Fuel Savings (relative to 2010 baseline)

for a fleet comprised entirely of next-generation aircraft. Some combination of petroleum and alternative fuels will power this fleet. Incorporating domestically produced alternative fuels, including 50-50 FT blends, offers a window to the likelihood of gaining independence from foreign oil.

A Petroleum Independent Air Force

In order for the Air Force to eliminate its vulnerability to an uncertain oil supply, it must satisfy two important criteria. First, the fuel that powers Air Force aviation must come from a reliable, sustainable source. It should be relatively immune to supply interruptions resulting from acts of terrorism or unfriendly foreign suppliers. In addition, the Air Force must have access to an energy supply with stable pricing to allow accurate budget forecasting and to minimize the need to divert execution year resources from other priorities. By breaking its dependence on the global oil market and incorporating domestic alternative fuels, *the Air Force* ***can*** *secure its energy independence in the 2030 timeframe.*

An analysis of next-generation aircraft helps support conclusions about overall Air Force petroleum use in 2030.[75] Considering the proportion of aviation fuel consumed by each mission area, projected improvements in next-generation aircraft lead to a fleet-wide average fuel savings of **40%** for relatively low risk technologies.[76] At a 40% reduction from today's levels, Air Force fuel requirements would drop from 2.5B gallons ($9B) in 2008, to 1.5B gallons ($5.4B) in 2030 (constant FY08 dollars). Additional savings due to efficient operations, advanced maintenance practices, and retirement of older aircraft would add to the windfall.

Supply Vulnerability

Fuel efficient technologies and alternative fuel sources are essential to securing the energy supply for Air Force aviation. With a more efficient fleet using a 50/50 blend of JP-8 and Fischer-Tropsch fuels, Air Force *petroleum* use could drop to 750 million gallons per year—only 30% of today's demand![77] This falls below the threshold of domestic oil production today and for the foreseeable future, and well below the total oil available from stable sources in the western hemisphere.[78] Though somewhat symbolic given the global nature of the petroleum

market, the ability to sustain Air Force petroleum needs with domestic sources is an attractive benchmark for policy makers. Improved fuel blends could cut petroleum use even further.

At these numbers, the Air Force would almost certainly eliminate its vulnerability to unstable foreign oil sources by 2030, but not without cost. Similar improvements within civil transportation would impose huge demands on the production of alternative fuels. With the Air Force representing only a small fraction of that demand (750 million gallons per year),[79] overall U.S. demand would be difficult to satisfy until supply chain and infrastructure investment caught up with the growing market. Energy independence, for the Air Force and the United States in general, is a responsibility that must be shared by the public and private sectors.

Cost Stability & the Air Force Budget

Today, the Air Force has reached a critical juncture that will determine its ability to project cost-effective power for the United States in the future. If aviation petroleum consumption remains at 2008 levels, the Department of Defense will be subjected to budget shocks of increasing magnitude and frequency whenever global oil demand exceeds production or when unstable suppliers seek an agenda contrary to U.S. interests.[80] Projected trends in the price of oil[81] could lead to debilitating increases in the Air Force fuel budget, up to $18 billion dollars per year in one worst-case estimate (Figure 13). Simply put, the cost of doing nothing is unacceptable.

Fortunately, by incorporating relatively low-risk, fuel-efficient technologies in next-generation aircraft powered by a 50-50 blend of JP-8 and F-T fuels, the Air Force could cut its petroleum requirements by 70%. After an immense national-level investment in production capacity and infrastructure, the price of alternative fuels should be relatively stable and considerably cheaper than petroleum. One analysis projects the cost of jet fuel derived from

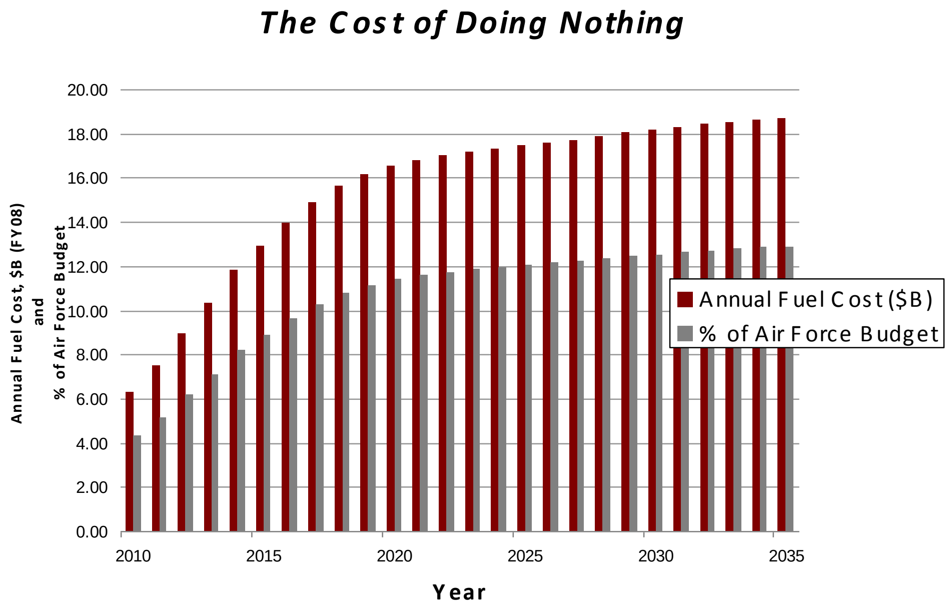

Figure 13: Future Air Force Fuel Budgets (The Cost of Doing Nothing)[85]

biomass and algae at less than $2 per gallon by 2025.[82] A 2001 Department of Energy (DoE) study estimated the price of coal-to-liquid (CTL) Fischer-Tropsch diesel at $1.24 per gallon before taxes.[83] A more recent DoE study set the threshold for CTL to compete with oil at $50 per barrel (of oil), well below projections through 2035.[84]

An Air Force that moves toward more efficient aviation powered by alternative fuels could look forward to increasingly affordable fuel budgets. One such path would capitalize on the Energy Plan goal of supplying half the Air Force fuel from 50-50 blends by 2016, while integrating technology into the legacy and next-generation fleets as it becomes available. The result is a substantial reduction in fuel cost against the "worst case" growth in oil prices (Figure 14). By 2030, the added impact of retiring older, less efficient airframes makes this course of action the clear favorite from a fiscal perspective.

Freeing up a large percentage of the Air Force fuel budget would give policy makers an opportunity to dedicate resources to other priorities, including force modernization and

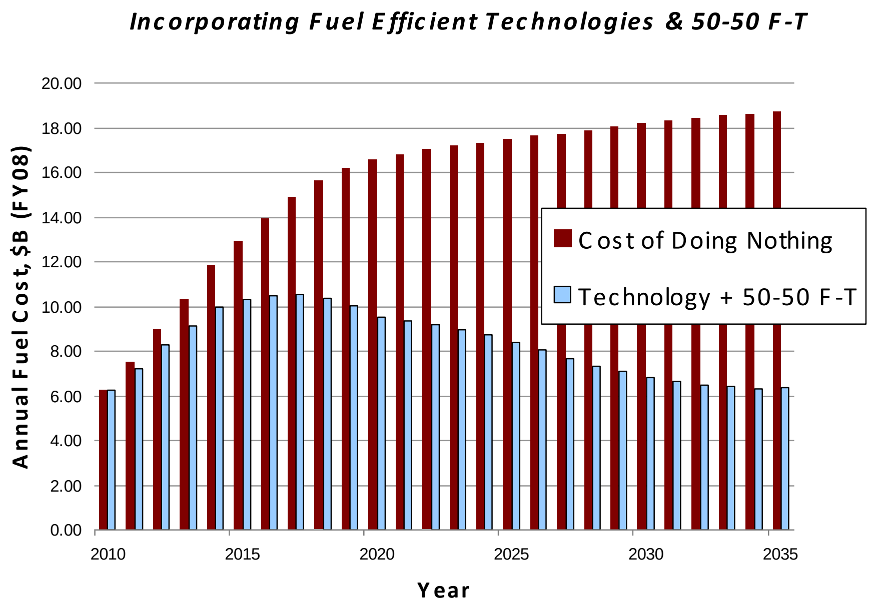

Figure 14: Future Air Force Fuel Budgets (Tech-Enabled Savings)[86]

infrastructure improvement. Compounded annually, the savings due to Air Force petroleum independence quickly adds up, exceeding a total of $120 billion by 2030 and $180 billion by 2035 (Figure 15). At a rough cost of $200 million per aircraft (FY08 dollars), $180 billion could purchase 900 next-generation mobility or fighter type aircraft, going a long way toward

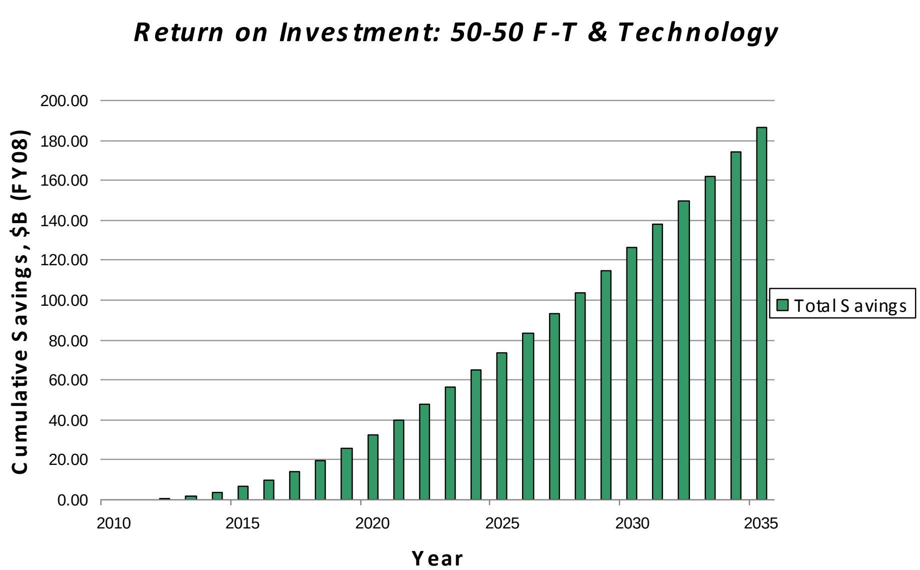

Figure 15: Payback for Petroleum Independence (Cumulative thru 2035)

recapitalizing an aging fleet. The savings could also be diverted to seed development of infrastructure and refinement capacity for alternative fuels. Such a commitment could fund about 30 F-T refineries, each producing 4 million gallons of fuel per day from coal or biomass.[87]

Operational Considerations

Beyond the obvious contribution toward a more secure, affordable fuel supply, next-generation technology offers the Air Force a chance to reduce operational complexity while sizing the fleet to capitalize on increased fuel efficiency. The trade space between fuel consumption, aircraft range, and payload capacity allows decision makers to reframe concepts of operation, particularly for the mobility mission.

The benefits of fuel efficiency are even more pronounced when range is the parameter of interest. Because a 50% reduction in fuel consumption effectively doubles aircraft range, the Breguet analysis recast in terms of range improvement provides some eye-opening results (Table 4). For example, a C-17 experiences an 80% improvement in cruise range for the same payload and fuel weight,[88] resulting in nearly half as many stops or aerial refuelings when transiting the

Design Factor	***Range Increase (%)***			
	Mobility	**Fighter/Attack**	**L-R Strike**	**ISR**
Structural Weight	34%	17%	19%	8%
Conventional Aerodynamics	18%	5%	11%	11%
Conventional Propulsion	18%	22%	25%	33%
Weight + Aero + Propulsion (Lower Risk)	**81%**	**49%**	**64%**	**59%**
Novel Configurations	33%	n/a	33%	33%
Hybrid Propulsion	25%	n/a	n/a	33%
Energy Capture/Storage	n/a	n/a	n/a	9%
Weight + Aero + Propulsion (Higher Risk)	**109%**	n/a	**87%**	**102%**

Table 4: Range Increase in 2030, by Mission Area (ref Appendix A)

globe. Less frequent refueling would enable a quicker, cheaper delivery of payload to theater with fewer ground support and air-refueling assets.

For a mission with unusually high payload demands, mobility planners could trade improvements in range or fuel consumption for added payload capacity. Doing so would allow fewer aircraft to deliver the same net payload to theater, offering an opportunity to re-task airlift assets elsewhere or shrink the overall airlift fleet and reduce the costs associated with logistics and manpower.

In a force extension scenario, increased fuel capacity would enable fewer tankers to escort a squadron of fighters or strategic air assets between theaters. Ideally, mobility aircraft of the future will fly to any point on the globe without aerial refueling or intermediate stops, but this capability is unlikely even in 2030, when high payload fractions will continue to exceed the limits of technology. Consequently, the next-generation tanker should remain among the Air Force's highest acquisition priorities, with the understanding that greater efficiency could empower a smaller fleet to perform the same workload.

Conclusions & Recommendations

Airpower's heavy reliance on foreign oil has exposed an Achilles' heel of the United States. Two criteria must be satisfied in order to eliminate this strategic vulnerability: supply security and price stability. Fortunately, a number of promising opportunities could reverse this unfortunate development, including the application of advanced technologies to Air Force aircraft. Through an intelligent blend of technology and a willingness to embrace alternative energy sources, *the Air Force* ***can*** *secure its energy independence in the 2030 timeframe.* Furthermore, fleet-wide improvements in efficiency should reduce Air Force fuel costs substantially.

An array of next-generation, fuel-efficient technologies could form the foundation of Air Force energy independence. Improvements generally occur in one of three categories:

1) *Structural Weight Reduction*
2) *Improved Aerodynamics*, and
3) *Enhanced propulsion efficiency*.

No single category stands out as "low hanging fruit," since each has significant technical hurdles to conquer. Yet all three show promise, and with sufficient investment in research and development, could yield ground-breaking advances in energy efficiency.

Along with a committed investment in relatively low-risk aircraft technologies, an aggressive move toward alternative fuels would transform Air Force energy use from a liability into a strategic advantage for the United States. Use of JP-8/Fischer-Tropsch fuel blends in a more fuel-efficient fleet could cut Air Force petroleum use 70% by 2030. At today's production levels, domestic petroleum sources would be sufficient to supply the remaining 30% assuming civil transportation embraces energy efficiency and alternative fuels with equal fervor. Success

in this effort would establish a reliable, sustainable source of jet fuel that is relatively immune to supply interruptions induced by governments or organizations unfriendly to the United States.

The fiscal benefits of petroleum independence are also substantial. Decoupling the Air Force budget from world oil and shifting toward a price-stable alternative—even if start-up costs are high—would reduce the risk of large, unforeseen liabilities throughout the year. Furthermore, alternative sources such as coal-to-liquid fuels could be considerably cheaper than petroleum in the 2030 timeframe, freeing up as much as $120 billion for other priorities between fiscal years 2010 and 2030.

Though discussed only qualitatively in this paper, a more fuel efficient fleet would also simplify Air Force operations, and offer decision makers a tradeoff between mission level performance and fleet size. The trade space between fuel consumption, aircraft range, and payload capacity also allows greater flexibility in mission planning and an opportunity to reframe concepts of operation, particularly for the mobility mission.

Although the scientific community has made considerable progress toward improving aircraft fuel efficiency, several areas of research merit immediate and aggressive investment:

(1) *Applied nanotechnology*. Nano-scale materials constitute the next hope for revolutionary improvements in structural strength and weight. Properly developed, high-strength carbon nano-tube reinforced composites could replace existing structural metals at half the weight of aluminum. Furthermore, nano-materials could one day enable the high-capacity batteries and energy capture techniques that help hybrid propulsion transform the aerospace industry.

(2) *Advanced propulsion concepts.* Conventional propulsion may appear to be in a period of technological leveling off, but experts believe there is still ample room for

improvement, as much as 20% in fuel efficiency by 2030. Hybrid propulsion, though facing its own challenges, could give next-generation aircraft the ability to operate with either jet fuel or electric power. Developing these concepts should be a cornerstone of Air Force modernization.

(3) *Novel aircraft configurations.* With only marginal improvements in conventional aerodynamics in recent years, now may be the time to embrace concepts such as the blended wing-body configuration. The Air Force must move beyond the stigma of unorthodox configurations to make the next big leap in fuel efficiency, at least 25% for the blended wing-body. Development would be costly, but the long-term benefits warrant the investment.

(4) *Alternative fuels.* The Air Force should stand firm on its goal of purchasing half its aviation fuel from 50-50 JP-8/Fischer-Tropsch sources by 2016. Furthermore, it should set additional targets that lead toward 100% use of blended fuels by 2021, and encourage the scientific community to develop even better blends which actually improve fuel efficiency. Alternative fuels constitute the one true linchpin to petroleum independence, and Air Force investment should reflect this fact.

Achieving a future without the specter of foreign oil will require a dedicated, well-resourced plan. Although private sector investment will prove vital to the effort, the Air Force cannot rely on commercial research and development to support all its mission areas. There will be many technical hurdles, program setbacks, and other bumps along the path to energy independence, but Air Force leadership should be committed to this goal. It has become a strategic imperative, and the time to act is now.

Appendix – Range/Fuel Calculations

Next-Gen Mobility Aircraft (C-17 baseline)

Design Optimization. Weight reduction = 10%.
Active Aeroelastic Control. Weight reduction = 5%.
Advanced Materials. Total structural weight reduction = 44%.*
Natural Laminar Flow. [see *adaptive compliant structures*].
Adaptive Compliant Structures. L/D increase = 15% (includes laminar flow effects).
Novel Configurations. L/D increase = 25% (not additive with other aero effects).
Conventional Gas Turbine Engines. TSFC reduction = 15%.
Hybrid Gas Turbine Engines. TSFC reduction = 20%.
Energy Capture/Storage. Probably not significant by 2030.
Alternative Fuels. Certified by 2011. Adequate supply is a concern.
Structural Weight Reduction:
C-17: W_{max} = 585,000 lb; W_0 = 277,000 lb; W_{Fmax} = 181,000 lb [89, 90]
W_P = 585,000 – 277,000 – 181,000 lb = 127,000 lb
Uninstalled weight of four PWF117-PW-100 engines: 4 x 7,100 lb = 28,400 lb [91]
Material fractions: 70% aluminum, 8% composites, 22% other [92]
Density of 70% SWNT relative to aluminum: 1200 kg/m^3 vs 2800 kg/(m^3) [93]
Weight reduction due to design optimization = 10%
Weight reduction due to active aeroelastic control = 5%
Airframe weight = W_0 - W_{Eng} = 277,000 – 28,400 = 248,600 lb
Optimized airframe weight = 248,600 lb x 85% = 211,300 lb

Aluminum: 147,900 lb
Composites: 16,900 lb
Other: 46,500 lb

Weight of CNRP to replace structural aluminum: 147,900 x (1200/2800) = 63,400 lb
Optimized airframe weight w/CNRP as primary structural material:

63,400 + 16,900 + 46,500 + 28,400 lb = 155, 200 lb

* Percent weight savings overall = (277,000 – 155,200) / 277,000 x 100% = 44%
Breguet W_0 impact (2010) = ln[1 + 181,000 / (127,000 + 277,000)] = .370
Breguet W_0 impact (2030) = ln[1 + 181,000 / (127,000 + 155,200)] = .496
Range increase due to W_0 reduction = .496 - .370 / .370 x 100% = 34%
Fuel savings due to W_0 reduction = .496 - .370 / .496 x 100% = 25%
Combined Effects (Lower-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 181,000 / (127,000 + 277,000)] = .370
Breguet total impact (2030) = (1/.85) x (1.15) x ln[1 + 181,000 / (127,000 + 155,200)] = .671
Total range increase = .671 - .370 / .370 x 100% = 81%
Total fuel savings = .671 - .370 / .671 x 100% = 45%
Combined Effects (Higher-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 181,000 / (127,000 + 277,000)] = .370
Breguet total impact (2030) = (1/.80) x (1.25) x ln[1 + 181,000 / (127,000 + 155,200)] = .775
Total range increase = .775 - .370 / .370 x 100% = 109%
Total fuel savings = .775 - .370 / .775 x 100% = 52%

Next-Gen Fighter (F-22 baseline)

Design Optimization. Weight reduction = 15%.
Active Aeroelastic Control. High wing loading and maneuvering load-factors probably eliminate this as a tangible benefit for fighter/attack aircraft.
Advanced Materials. Total structural weight reduction = 18%.**
Natural Laminar Flow. A wide range of airspeeds limits time on the design condition. L/D increase = 5%
Adaptive Compliant Structures. Not practical due to mission requirements.
Novel Configurations. Not practical due to payload and maneuverability requirements.
Conventional Gas Turbine Engines. TSFC reduction = 18% (assumes A/B use consumes 20% of fuel load).
Hybrid Gas Turbine Engines. Not practical due to requirement for low-planform engine and lack of battery storage space.
Energy Capture/Storage. Not practical due to low fraction of captured energy.
Alternative Fuels. Certified by 2011. Adequate supply is a concern.
Structural Weight Reduction:
F-22A: W_{max} = 83,500 lb; W_0 = 43,300 lb; W_{Fmax} = 18,000 lb [94]
W_P = 83,500 – 43,300 – 18,000 lb = 22,200 lb
Combat loadout: 43,300 + 18,000 + 3,000 (2xA120, 2xA9X, 2xGBU32) = 64,300 [95]
Uninstalled weight of two F119-PW-100 engines: 2 x 4,100 lb = 8,200 lb
(estimate T/W = 8.5:1 [PW-229's is 7.8:1], and T = 35,000 lb) [96, 97]
Material fractions: 15% aluminum, 24% composites, 61% other [98]
Density of 70% SWNT relative to aluminum: 1200 kg/m^3 vs 2800 kg/(m^3) [99]
Weight reduction due to design optimization = 15%
Weight reduction due to active aeroelastic control = 0%
Airframe weight = W_0 - W_{Eng} = 43,300 – 8,200 = 35,100 lb
Optimized airframe weight = 35,100 lb x 85% = 29,800 lb
Aluminum: 4,500 lb
Composites: 7,200 lb
Other: 18,200 lb
Weight of CNRP to replace structural aluminum: 4,500 x (1200/2800) = 1,900 lb
Optimized airframe weight w/CNRP use:
1,900 + 7,200 + 18,200 + 8,200 lb = 35,500 lb
** Percent weight savings overall = (43,300 – 35,500) / 43,300 x 100% = 18%
Breguet W_0 impact (2010) = ln[1 + 18,000 / (3,000 + 43,300)] = .328
Breguet W_0 impact (2030) = ln[1 + 18,000 / (3,000 + 35,500)] = .384
Range increase due to W_0 reduction = .384 - .328 / .328 x 100% = 17%
Fuel savings due to W_0 reduction = .384 - .328 / .384 x 100% = 15%
Combined Effects (Lower-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 18,000 / (3,000 + 43,300)] = .328
Breguet total impact (2030) = (1/.82) x (1.05) x ln[1 + 18,000 / (3,000 + 35,500)] = .491
Total range increase = .491 - .328 / .328 x 100% = 49%
Total fuel savings = .491 - .328 / .491 x 100% = 33%

Next-Gen Long-Range Strike (B-2 baseline)

Design Optimization. Weight reduction = 10%.
Active Aeroelastic Control. Weight reduction = 15%.
Advanced Materials. Total structural weight reduction = 27%.***
Natural Laminar Flow. L/D increase = 10%.
Adaptive Compliant Structures. Not practical due to mission requirements.
Novel Configurations. Options limited by payload and maneuverability requirements.
L/D increase could = 25% (not additive with other aero effects).
Conventional Gas Turbine Engines. TSFC reduction = 20%.
Hybrid Gas Turbine Engines. Not practical due to requirement for low-planform engine.
Energy Capture/Storage. Not practical due to low fraction of captured energy.
Alternative Fuels. Certified by 2011. Adequate supply is a concern.
Structural Weight Reduction:
B-2A: W_{max} = 336,500 lb; W_0 = 160,000 lb; W_{Fmax} = 167,000 lb; W_P = 40,000 lb [100]
Uninstalled weight of four F118-GE-100 engines: 4 x 3,200 lb = 12,800 lb [101]
Material fractions: ~20% aluminum/titanium, ~80% composites [102]
Density of 70% SWNT relative to aluminum: 1200 kg/m^3 vs 2800 kg/(m^3) [103]
Weight reduction due to design optimization = 10%
Weight reduction due to active aeroelastic control = 15%
Airframe weight = W_0 - W_{Eng} = 160,000 – 12,800 = 147,200 lb
Optimized airframe weight = 147,200 lb x 75% = 110,400 lb
Aluminum (~10%): ~11,000 lb
Titanium (~10%): ~11,000 lb
Composites: 88,300 lb
Weight of CNRP to replace structural aluminum: 11,000 x (1200/2800) = 4,700 lb
Optimized airframe weight w/CNRP use:
4,700 + 11,000 + 88,300 + 12,800 lb = 116,800 lb
*** Percent weight savings overall = (160,000 – 116,800) / 160,000 x 100% = 27%
Breguet W_0 impact (2010) = ln[1 + 167,000 / (40,000 + 160,000)] = .607
Breguet W_0 impact (2030) = ln[1 + 167,000 / (40,000 + 116,800)] = .725
Range increase due to W_0 reduction = .725 - .607 / .607 x 100% = 19%
Fuel savings due to W_0 reduction = .725 - .607 / .725 x 100% = 16%
Combined Effects (Lower-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 167,000 / (40,000 + 160,000)] = .607
Breguet total impact (2030) = (1/.80) x (1.10) x ln[1 + 167,000 / (40,000 + 116,800)] = .997
Total range increase = .997 - .607 / .607 x 100% = 64%
Total fuel savings = .997 - .607 / .997 x 100% = 39%
Combined Effects (Higher-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 167,000 / (40,000 + 160,000)] = .607
Breguet total impact (2030) = (1/.80) x (1.25) x ln[1 + 167,000 / (40,000 + 116,800)] = 1.133
Total range increase = 1.133 - .607 / .607 x 100% = 87%
Total fuel savings = 1.133 - .607 / 1.133 x 100% = 46%

Next-Gen ISR Aircraft (MQ-9 baseline)

Design Optimization. Weight reduction = 10%.
Active Aeroelastic Control. Weight reduction = 5%.
Advanced Materials. Total structural weight reduction = 13%.****
Natural Laminar Flow. L/D increase = 10%.
Adaptive Compliant Structures. Not practical due to mission requirements.
Novel Configurations. L/D increase = 25%.
Conventional Gas Turbine Engines. TSFC reduction = 25%.
Hybrid Gas Turbine Engines. Same benefit as conventional (25%); MQ-9 battery use not practical due to weight penalty.
Energy Capture/Storage. Wing span = 66 ft; wing chord ~ 3 ft; wing area ~ 200 (ft^2) [104]; Using NASA's Centurion as baseline: 31,000W / 1648 ft^2 = 19 W / ft^2 of solar panel today [105]; 10-fold increase if high-risk research pays off → 190 W / ft^2, or ~ 38 kW for the MQ-9 wing with high-efficiency, flexible panels; 3/4 power setting (estimate), the TPE-331 draws ~ 500 kW (.75 x 900 shp) [106]; 38kW/500kW = 8% improvement in TSFC
Alternative Fuels. Certified by 2011. Adequate supply is a concern.
Structural Weight Reduction:
MQ-9: W_{max} = 10,500 lb; W_0 = 4,900 lb; W_{Fmax} = 4,000 lb; W_{Pmax} = 3,750 lb [107]
W_P = 10,500 – 4,900 – 4,000 lb = 1,600 lb
Uninstalled weight of Honeywell TPE331-10GD turboprop engine: 400 lb [108]
Material fractions: 8% aluminum/steel/titanium, 92% composites [109]
Density of 70% SWNT relative to aluminum: 1200 kg/m^3 vs 2800 kg/(m^3) [110]
Weight reduction due to design optimization = 10%
Weight reduction due to active aeroelastic control = 5%
Airframe weight = W_0 - W_{Eng} = 4,900 – 400 = 4,500 lb
Optimized airframe weight = 4,500 lb x 85% = 3,830 lb
Aluminum (~5%): 180 lb; Composites: 3630 lb
Savings due to use of CNRP to replace structural aluminum: negligible
Optimized airframe weight (no CNRP use): 3,830 + 400 lb = 4,230 lb
**** Percent weight savings overall = (4,900 – 4,230) / 4,900 x 100% = 13%
Breguet W_0 impact (2010) = ln[1 + 4,000 / (1,600 + 4,900)] = .480
Breguet W_0 impact (2030) = ln[1 + 4,000 / (1,600 + 4,230)] = .520
Range increase due to W_0 reduction = .520 - .480 / .480 x 100% = 8%
Fuel savings due to W_0 reduction = .520 - .480 / .520 x 100% = 7.5%
Combined Effects (Lower-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 4,000 / (1,600 + 4,900)] = .480
Breguet total impact (2030) = (1/.75) x (1.10) x ln[1 + 4,000 / (1,600 + 4,230)] = .763
Total range increase = .763 - .480 / .480 x 100% = 59%
Total fuel savings = .763 - .480 / .763 x 100% = 37%
Combined Effects (Higher-Risk Technologies)
Breguet total impact (2010) = (1/1) x (1) x ln[1 + 4,000 / (1,600 + 4,900)] = .480
Breguet total impact (2030) = (1/.67) x (1.25) x ln[1 + 4,000 / (1,600 + 4,230)] = .971
Total range increase = .971 - .480 / .480 x 100% = 102%
Total fuel savings = .971 - .480 / .971 x 100% = 51%

End Notes

[1] Adm Michael G. Mullen, chairman, Joint Chiefs of Staff (address, Energy Security Forum, Washington, DC, 13 October 2010), http://www.jcs.mil/speech.aspx?ID=1472.

[2] United States Census Bureau, "US and World Population Clocks," http://www.census.gov/main/www/popclock.html (accessed 29 November 2010). At 17:36 UTC, population estimates were 310,812,888 (US) and 6,884,646,070 (world).

[3] United States Department of Energy, Energy Information Administration, "Oil and Petroleum Products: Data and Statistics," http://www.eia.doe.gov/energyexplained/index.cfm?page=oil_home#tab2 (accessed 29 November 2010). In 2009, the U.S. consumed 18.7 million barrels of petroleum per day.

[4] Ibid. Total world petroleum consumption in 2009 was 84.2 million barrels per day.

[5] United States Department of Energy, Energy Information Administration, "How dependent are we on foreign oil?" http://www.eia.doe.gov/energy_in_brief/foreign_oil_dependence.cfm (accessed 29 November 2010). U.S. dependence on net petroleum imports was 52% in 2009. DoE projects that U.S. dependence on foreign oil could decrease to 40% by 2030 based on aggressive domestic production and increased use of coal-to-liquids and biofuel alternatives. Earlier Department of Energy studies predicted opposite trends in imported oil.

[6] Mullen (address, Energy Security Forum)

[7] Department of Energy, "How dependent are we on foreign oil?"

[8] United States Department of Energy, Energy Information Administration, *Annual Energy Outlook 2010*, http://www.eia.doe.gov/oiaf/aeo/economic.html (accessed 29 November 2010). Range of projected prices in 2030 was from a low of $50 per barrel to a high of approximately $205.

[9] Mullen (address, Energy Security Forum)

[10] Dennis Bushnell (lecture, Center for Strategy and Technology, Air War College, Montgomery, AL, 9 November 2010).

[11] Otto Kreisher, "Move That Gas," *Air Force-Magazine.com*, September 2010, http://www.airforce-magazine.com/MagazineArchive/Pages/2010/September%202010/0910gas.aspx.

[12] United States Air Force, *Air Force Energy Plan 2010*, http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf, 4.

[13] United States Air Force, *2008 Infrastructure Energy Strategic Plan, 9-10,* http://www.afcesa.af.mil/shared/media/document/AFD-081029-038.pdf.

[14] United States Air Force, *Air Force Energy Plan 2010*, 4.

[15] United States Air Force, Scientific Advisory Board, *Technology Options for Improved Air Vehicle Efficiency,* SAB-TR-06-04 (Washington DC: United States Air Force Scientific Advisory Board, May 2006), 14. Figures based on average fuel use from FY98-04.

[16] United States Air Force, *Air Force Energy Plan 2010*, 7.

[17] Ryan W. Plumley and Dieter Multhopp, "Developing Technology for Efficient Air Mobility" (applied aerodynamics Revolutionary Configurations for Energy Efficiency (RCEE) briefing, Air Vehicle Technology Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, 2010), slide 11.

[18] "News Notes," *AIR FORCE Magazine*, November 2010, 26.

[19] United States Air Force, *Air Force Energy Plan 2010*, 8.

[20] Ray Kurzweil, *The Singularity is Near* (New York, NY: Penguin Group, 2005), Kindle e-book, location 1090.

[21] Scientific Advisory Board, *Technology Options for Improved Air Vehicle Efficiency*, 16.

[22] Ibid., 16.

[23] Ibid., 1.

[24] Scientific Advisory Board, *Technology Options for Improved Air Vehicle Efficiency*, 36. Lockheed Martin's Robust Composite Sandwich Structure (ROCSS) program achieved a 36% structural weight savings over the F-22A baseline. The SAB expects these methods to yield a 10-15% reduction in empty weight of future tactical airframes, with similar gains possible on transport aircraft.

[25] Robert A. Rowe (Lockheed Martin Corporation), "Rapid Development of the X-55A/Advanced Composite Cargo Aircraft (ACCA) and Initial Flight Test Results" (paper presented at 54th SETP Symposium & Banquet, Anaheim, CA, September 2010), 1-5. The X-55A, an Air Force sponsored program, demonstrated the first unitized composite structure for a large aircraft (Do-328j). In the interest of cost and time, program scope was limited to the fuselage and vertical tail (challenging and expensive to fabricate from composites), successfully building a two-piece out-of-autoclave structure with a 90% reduction in parts and estimated 50-90% reduction in manufacturing costs.

[26] Leland Nicolai, Keith Hunten, Scott Zink, and Pete Flick, "System Benefits of Active Flutter Suppression for a SensorCraft-Type Vehicle" (paper presented at the 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, Forth Worth, TX, September 2010), 1. The analysis looked at a high-altitude, high-dwell UAV with a high-aspect ratio flying wing

configuration. It determined that active flutter suppression would allow a structural weight reduction from 18,000 to 14,500 pounds (19%).

[27] Assuming a wing weight fraction of 20-25%, typical of conventional tube & wing configurations.

[28] The Boeing Company, "787 Dreamliner," http://www.boeing.com/commercial/787family/background.html (accessed 4 December 2010). Boeing has announced that as much as 50 percent of the primary structure, including the fuselage and wing, on the 787 will be made of composite materials.

[29] Jeff Sloan, "Skinning the F-35," http://www.compositesworld.com/articles/skinning-the-f-35-fighter (accessed 25 October 2010).

[30] Lynn E. Foster, *Nanotechnology: Science, Innovation, and Opportunity* (Upper Saddle River, NJ: Prentice Hall, 2006), 148-150. Section contributed by Brent Segal (Echelon Ventures) describes CNT properties as "remarkable strength, high elasticity, and large thermal conductivity and current density."

[31] Nanocomp Technologies, Inc, "Nanocomp – Technology," http://www.nanocomptech.com/html/nanocomp-technology.html (accessed 4 December 2010). Web site touts CNT yarn properties as:
"High Strength – our spun conductive yarns exhibit breaking strengths up to 3 GPa expressed or in other terms: 1.5 Nt/Tex or 450,000 psi and with fracture toughness that is higher than aramids (such as Kevlar® or Twaron®). Our CNT sheets have breaking strengths, without binders, that range from 500 MPa to 1.2 GPa depending upon tube orientation. Aluminum breaks at 500 MPa, carbon steel breaks around 1 GPa. Extremely Lightweight – Less than half the weight of aluminum"

[32] Bushnell (lecture, center for strategy and technology).

[33] Sarah E. O'Donnell, Kevin R. Sprong, and Brennan M. Haltli, "Potential Impact of Carbon Nanotube Reinforced Polymer Composite on Commercial Aircraft Performance and Economics" (paper presented at the 4th AIAA Aviation Technology, Integration and Operations (ATIO) conference, Chicago, IL, September 2004), 1-4. This methodology used a baseline CNRP which possessed 70% by volume single-walled CNTs. Its properties included a density of 1200 kg/m3 and tensile strength of 6620 MPa, as opposed to carbon fiber composites (1600 kg/m3 and 1500 MPa) and aluminum (2780 kg/m3 and 480 MPa). CNRPs were used to replace structural aluminum, one-for-one by volume.

[34] Robert A. Rowe, "Rapid Development of the X-55A," 8-9. The X-55A demonstrated the first unitized composite structure for a large aircraft (Do-328j). Program scope was limited to the fuselage and vertical tail (challenging and expensive to fabricate from composites), successfully building a two-piece out-of-autoclave structure with a 90% reduction in parts and estimated 50-90% reduction in manufacturing costs.

[35] Carl P. Tilmann and Peter M. Flick, "High-Altitude Long Endurance Technologies for SensorCraft," RTO-MP-104 (paper presented at RTO AVT Symposium, Brussels, Belgium, April 2003), 14.

[36] Plumley and Multhopp, "Developing Technology for Efficient Air Mobility," slide 9.

[37] Eric D. Brown, Sean R. Wakayama, and Zachary C. Hoisington (the Boeing Company), *Revolutionary Configurations for Energy Efficiency, Volume 1* (AFRL-RB-WP-TR-2010-XXXX (not yet numbered), Wright Patterson AFB, OH: Air Vehicles Directorate, December 2010), 37.

[38] Sridhar Kota, Russell Osborn, Gregory Ervin, Dragan Maric, Peter Flick, and Donald Paul, "Mission Adaptive Compliant Wing – Design, Fabrication and Flight Test" (unpublished technical paper, Ann Arbor, MI: FlexSys Inc, n.d.), 2.

[39] Ibid., 1.

[40] NASA Dryden Flight Research Center, "Past Projects: AD-1," http://www.nasa.gov/centers/dryden/history/pastprojects/AD1/index.html (accessed 5 December 2010).

[41] Plumley and Multhopp, "Developing Technology for Efficient Air Mobility," slide 10. The initial goal of the program to demonstrate a robust control system up to wing stall has been accomplished (a first for this type of aircraft); modifications for achieving efficiency and environmental goals are currently in progress (as of Jan 2011).

[42] Ryan W. Plumley and Dieter Multhopp, "Energy Efficient Air Mobility: How far can we go?" (AIAA 2009-4313, paper presented at 27th AIAA Applied Aerodynamics Conference, San Antonio, TX, June 2009), 5-6. The Cambridge-MIT Institute's SAX-40 design is another BWB example. The concept has wide applicability to transports, tankers, and bombers; also high-dwell aircraft such as ISR unpiloted air vehicles (author added). The traditional cylindrical fuselage is replaced by an airfoil shape. Less surface area reduces drag; payload weight is distributed across the wing, reducing structural weight requirements.

[43] NASA Dryden Flight Research Center, "Fact Sheets: X-48B Blended Wing-Body," http://www.nasa.gov/centers/dryden/news/FactSheets/FS-090-DFRC.html (accessed 5 December 2010).

[44] Scientific Advisory Board, *Technology Options for Improved Air Vehicle Efficiency*, 17.

[45] Ibid., 17-19.

[46] Ibid., 17.

[47] Multhopp, Dieter, Chris Norden, Jeff Stricker, Monica Stucke, and Edward DePalma. "Fuel Efficiency and Alternative Fuel Source Initiatives" (AFRL briefing to SAB Fuel Efficiency Study, Wright Patterson AFB, OH, 10 November 2005).

[48] Timothy J. Lewis, chief, Engine Integration and Assessment Branch, Turbine Engine Division, Propulsion Directorate, AFRL, Wright-Patterson AFB, OH, to the author, e-mail, 17-18 November 2010.

[49] General Electric, "GE Awarded Advanced Affordable Turbine Engine Contract by U.S. Army," Press release, 27 November 2007, http://www.geae.com/aboutgeae/presscenter/military/military_20071121.html (accessed 6 December 2010). U.S. Army goal is a 25% reduction in TSFC for a 3000 shaft-horsepower class engine. The MQ-9 engine is rated at approximately 900 shaft-horsepower (US Air Force Fact Sheet).

[50] United States Air Force, *Air Force Acquisition & Technology Energy Plan 2010*, http://www.safie.hq.af.mil/shared/media/document/AFD-091208-028.pdf, 19. Objective 2.3 calls for developing advanced technologies to increase the range and loiter capability of aircraft.

[51] Boeing Company, "Feature Story: Envisioning tomorrow's aircraft," http://www.boeing.com/Features/2010/06/corp_envision_06_14_10.html (accessed 18 November 2010).

[52] Warwick, Graham, "Airliners in 2030: Propulsion Options," *Aviation Week and Space Technology*, 14 May 2010, http://www.aviationweek.com/aw/blogs/aviation_week/on_space_and_technology/index... (accessed 27 October 2010).

[53] Plumley and Multhopp, "Energy Efficient Air Mobility: How far can we go?" 6. Plumley remark (7 Feb 2011): Efficiency of the combined propulsion/electrical system becomes an important metric when evaluating hybrid propulsion; it remains an open question that will require additional investigation.

[54] MicroLink Devices, Inc, "Development and Demonstration of High Efficiency, Lightweight, Flexible Solar Panels for Unmanned Aerial Vehicles" (technical proposal and statement of work (prepared by UES, Inc), Dayton, OH, 5 February 2010), p 3.

[55] Eric D. Brown, Sean R. Wakayama, and Zachary C. Hoisington (the Boeing Company), *Revolutionary Configurations for Energy Efficiency*, 16.

[56] Ibid., 3, 8. Raven UAV demo sponsored by AFRL is expected to be approximately energy neutral in full sunlight. Excess energy will be used to recharge batteries.

[57] Plumley and Multhopp, "Energy Efficient Air Mobility: How far can we go?" 6.

[58] Nicholas V. Caldwell, Robert W. Parker, and Michael Karam, "Revolutionary Configuration for Energy Efficiency Program (RCEE): Propulsion Summary" (Northrop-Grumman program update to AFRL, Wright-Patterson AFB, OH, 5 October 2010).

[59] Plumley and Multhopp, "Energy Efficient Air Mobility: How far can we go?" 6.

[60] MicroLink Devices, Inc, "Development and Demonstration of High Efficiency, Lightweight, Flexible Solar Panels," 3. The amount of solar energy captured in lower light or cloudy conditions is approximately cut in half.

[61] Linda A. Cicero, "Farm Report: More Power to Them," *Stanford Magazine*, November/December, 2010, 36-7.

[62] Louis Bergeron, "Solar Cells Thinner than Wavelengths of Light Hold Huge Power Potential, Stanford Researchers Say," *Stanford Report*, 27 September 2010, http://news.stanford.edu/news/2010/september/nanoscale-solar-cells-092710.html (accessed 4 November 2010).

[63] MicroLink Devices, Inc, "Development and Demonstration of High Efficiency, Lightweight, Flexible Solar Panels," 20. Environmental stresses include humidity, temperature extremes, and ultraviolet radiation, to name a few.

[64] "Battery Energy -- What Battery Provides More?" http://www.allaboutbatteries.com/Battery-Energy.html (accessed 8 December 2010).

[65] Odile Bertoldi and Sebastien Berger, "Observatory Nano: Report on Energy," draft report for European Commission, 8 June 2009, 5, http://www.observatorynano.eu/project/filesystem/files/WP2_5Energy_5Batteries&Supercapacitors.pdf (accessed 8 December 2010).

[66] Eric D. Brown, Sean R. Wakayama, and Zachary C. Hoisington (the Boeing Company), *Revolutionary Configurations for Energy Efficiency, Volume 1*, 15.

[67] Scientific Advisory Board, *Technology Options for Improved Air Vehicle Efficiency*, 40.

[68] Edwards, Tim, Cliff Moses, and Fred Dryer, *Evaluation of Combustion Performance of Alternative Aviation Fuels* (AIAA Report 2010-7155, 46th AIAA/ASME/SAE/ASEE Joint Propulsion conference & exhibit, Nashville, TN, 25-28 July, 2010), 2-3.

[69] "News Notes," *AIR FORCE Magazine*, November 2010, 26.

[70] Danigole, Mark S, *Biofuels: An Alternative to US Air Force Petroleum Fuel Dependency* (Occasional Paper No. 62 (edited by John P. Geis), Maxwell AFB, AL: Center for Strategy and Technology, Air War College, December 2007), 35.

[71] United States Department of Defense, "Aircraft Investment Plan, Fiscal Years (FY) 2011-2040" (submitted with the FY 2011 Budget, Washington DC: February, 2010), 4-5. http://www.militarytimes.com/static/projects/pages/30yearaviation.pdf. According to the plan, persistent ISR, airlift, fighter/attack, and long-range strike are the four principle DoD aircraft investment areas from FY2011-2040.

[72] Author's simplifying assumptions for the mission-area analysis include, but are not limited to, the following:
(1) 2010 configurations constitute the technology "baseline" against which improvements in fuel efficiency are measured.
(2) Percent reduction in fuel use due to engine efficiency applies to all mission phases (start, taxi, takeoff, climb, cruise…). This is a reasonable assumption as long as the relative time in each phase (especially with high power settings) doesn't change dramatically between now and 2030.
(3) Improvements in each design parameter (L/D, W_O) constitute averages across the typical mission profile.
(4) Assumptions that govern the Breguet range equation apply.
(5) Breguet range equation initial weights: max fuel weight, standard empty weight, and payload sized to meet aircraft gross weight limits (if air refueling capable, max payload or typical combat payload was used).
(6) The Breguet equation is used to generalize range & fuel trends across all mission elements, even though its use should be limited to cruise for actual range computations. As with assumption (2) above, this should be a reasonable assumption as long as time spent in each mission phase is typical of today's airframes.

Author's disclaimers for the mission-area analysis:
(1) Some sources reference in this study examined typical mission profiles; some did not.
(2) This report focuses on fuel efficiency through the application of technology; improvements in operations & maintenance were not considered

[73] Adding individual effects of each technology category would overstate the aggregate increase in fuel efficiency. For structural technologies, the effects of design optimization and aeroelastic control were added prior to incorporating nano-scale composites as a multiplier to the enhanced airframe. Within the aerodynamics category, laminar flow was assumed to be a by-product of adaptive structures (i.e., the effects were not added on airframes for which both were viable). Novel configurations such as the blended wing-body were treated as stand-alone concepts incorporating the latest in aerodynamic efficiency. Propulsive effects were attributable to advances in either conventional or hybrid gas-turbine technology. Hybrid or captured energy effects were addressed separately.

[74] The "lower-risk" category includes all structural technologies, conventional aerodynamic improvements, and enhancements to conventional gas-turbine propulsion. The "higher-risk" category also includes structural technologies, but incorporates novel aerodynamic configurations, hybrid gas-turbine engines, and where applicable, energy capture. The "higher risk" science involved concepts not generally suited to fighter type aircraft.

[75] Author's simplifying assumptions for the fleet-wide analysis include, but are not limited to, the following:
(1) 2010 technology constitutes the "baseline" against which fleet-wide gains in fuel efficiency are measured. Figures from FY 2008 will be used in the actual comparison.
(2) In 2030, Air Force mission areas will have roughly the same proportion as in 2010.
(3) In 2030, the inventory will have roughly the same proportion of aircraft as in 2010.

(4) In 2030, Air Force global commitments will be roughly the same as in 2010.

Author's disclaimers for the fleet-wide analysis:
(1) There exists wide variability in fuel consumption across the 2010 inventory.
(2) Replacing technology of the 1950s-1970s with new fuel-efficient aircraft in 2030 will yield additional benefits not addressed in this analysis.

[76] Weight fuel efficiency for lower-risk technologies: .542*45% + (.301+.042)*33% + .071*39% + .044*37% = **40%** (trainers treated as fighters); higher-risk technologies: .542*52% + (.301+.042)*33% + .071*46% + .044*51% = **45%**. The higher-risk analysis lacks fidelity due to the uncertain nature of those technologies. It is possible that a higher risk investment strategy could yield fuel savings in excess of 45%. In the interest of setting conservative expectations, the remainder of this paper considers only lower risk technologies.

[77] At 60% of today's needs, a 50/50 JP-8/F-T blend would require approximately 30% of today's petroleum (750 million gallons) supplemented by an equal quantity of F-T fuel.

[78] Department of Energy, "How dependent are we on foreign oil?" Total supply available from domestic and stable Western sources is approximately 70% of global supply (= 45% * 50% + 50%).

[79] See note 76.

[80] James T. Bartis and Lawrence Van Bibber, "Alternative Fuels for Military Applications," (Santa Monica, CA: RAND National Defense Research Institute, 2011), xv. This report provides another excellent discussion of the national benefits of petroleum independence.

[81] Department of Energy, *Annual Energy Outlook 2010.*

[82] Danigole, *Biofuels: An Alternative*, 35, 37.

[83] National Center for Policy Analysis, "Turning Coal into Liquid Fuel" (research analysis No. 656, 1 May 2009), http://www.ncpa.org/pub/ba656 (accessed 13 December 2010).

[84] United States Department of Energy, *Coal to Liquids Technology* (Washington, DC: Office of Fossil Energy, March 2008), http://fossil.energy.gov/programs/fuels/publications/2-28-08_CTL_Brochure.pdf.
Also, Department of Energy, *Annual Energy Outlook 2010.*

[85] Annual fuel costs based on 2008 consumption levels and DoE oil price projections (reference Figure 2 and end note 8). Budget percentages assume an annual Air Force budget of $145B (constant FY08 dollars), which generally reflects recent years.

[86] Assumes a conservative price of $2/gal (FY08 dollars) for CTL fuels. Increases the percentage of 50-50 fuels according to the Air Force Energy Plan goal of purchasing half its fuel as 50-50 blends by 2016, continuing so that all fuels are 50-50 by 2021. Incorporates fuel

efficient technologies beginning at 2020 and continuing through 2030. Although Figure 14 is based on DoE's "high" estimate for oil prices, a similar benefit would be gained if oil were to follow the more benign "baseline" in terms of cost growth. Conversion to F-T use provides some near-term benefit since CTL and biomass F-T fuels are expected to be considerably cheaper. The gap widens as petroleum costs continue to rise, then widens further as fuel efficient technologies proliferate into the inventory.

[87] Danigole, *Biofuels: An Alternative,* 35.

[88] Due to Breguet equation constraints, the actual range improvement would be somewhat reduced (due to the penalty of carrying fuel from takeoff elevation to cruise altitude), unless the total fuel weight were achieved through air-refueling at cruise altitude.

[89] Boeing Company, "C-17 Globemaster III," http://www.boeing.com/history/mdc/c-17.htm (accessed 9 December 2010).

[90] Aerospaceweb.org, "C-17 Globemaster III," http://www.aerospaceweb.org/aircraft/transport-m (accessed 9 December 2010).

[91] Pratt & Whitney, "F-117 C-17 Characteristics," http://www.pw.utc.com/Products/Military/F117 (accessed 9 December 2010).

[92] Air Force Technical Order (TO) 00-105E-9, *Aerospace Emergency Rescue and Mishap Response Information, Revision 11,* 1 February 2006, C-17A.10, http://www.0x4d.net/files/AF1/R11%20Segment%201.pdf

[93] O'Donnell, Sprong, and Haltli, "Potential Impact of Carbon Nanotube Reinforced Polymer Composites," 1-4.

[94] Air Force Fact Sheet, "F-22 Raptor," http://www.af.mil/information/factsheets/factsheet.asp?id=199 (accessed 9 December 2010).

[95] Ibid.

[96] Ibid.

[97] Pratt & Whitney, "Pratt & Whitney's F-100-PW-229," White Paper, 17 June 2008, http://www.pw.utc.com/StaticFiles/Pratt%20&%20Whitney%20New/Media%20Center/Assets/1%20Static%20Files/Docs/F100-PW-229-white-paper.pdf (accessed 9 December 2010).

[98] Air Force Technical Order (TO) 00-105E-9, *Aerospace Emergency Rescue and Mishap Response Information, Revision 11,* 1 February 2006, F/A-22A.12, http://www.0x4d.net/files/AF1/R11%20Segment%201.pdf

[99] O'Donnell, Sprong, and Haltli, "Potential Impact of Carbon Nanotube Reinforced Polymer Composites," 1-4.

[100] Air Force Fact Sheet, "B-2 Spirit," http://www.af.mil/information/factsheets/factsheet.asp?id=82 (accessed 9 December 2010).

[101] General Electric, "GE Aviation, Comparison Chart: Turbofans," http://www.geae.com/engines/military/comparison_turbofan.html (accessed 9 Dec 2010).

[102] Walter J. Boyne, *Beyond the Wild Blue: A History of the U.S. Air Force* (New York, NY: St Martin's Griffin, 1997), 260.

[103] O'Donnell, Sprong, and Haltli, "Potential Impact of Carbon Nanotube Reinforced Polymer Composites," 1-4.

[104] Air Force Fact Sheet, "MQ-9 Reaper," http://www.af.mil/information/factsheets/factsheet.asp?id=6405 (accessed 11 December 2010).

[105] NASA Fact Sheet, "Centurion," http://www.nasa.gov/centers/dryden/news/FactSheets/FS-056-DFRC.html
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[106] Air Force Fact Sheet, "MQ-9 Reaper," http://www.af.mil/information/factsheets/factsheet.asp?id=6405 (accessed 11 December 2010).

[107] Ibid.

[108] Honeywell Aerospace Brochure, "TPE331-10 Turboprop Engine," http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/BA_brochures-documents/TPE331-10_PredatorB_0292-000.pdf (accessed 12 February 2011).

[109] Air Force Technical Order (TO) 00-105E-9, *Aerospace Emergency Rescue and Mishap Response Information, Revision 11*, 1 February 2006, MQ-1/RQ-1.7, http://www.0x4d.net/files/AF1/R11%20Segment%201.pdf

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